Effects of Delays on Depth Perception by Motion Parallax in Virtual Environment

by

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B.S. Biomedical Engineering, Shanghai Jiao Tong University, 1995

Submitted to the Department of Electrical Engineering and Computer Science in partial fulfillment of the requirements for the degree of

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Jan 28, 1999

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Abstract

Virtual Environment systems (VEs) impose alterations on normal sensory-motor loops. It's important to know the effects of these alterations in order to make rational choices in system design. This thesis focuses on the effects of time delays introduced in VEs on depth perception by motion parallax.

The experimental set-up is composed of a personal computer and a headtracker that tracks the movement of the head and sends that information to the computer. The stimuli are computer-generated random-dot patterns that can be updated according to each movement of the observer to simulate the relative movement produced by three dimensional sine-wave surfaces.

Two two-alternative-forced-choice experiments were performed with 6 human subjects to investigate the effects of delays on depth perception by motion parallax. Results are discussed and ideas for future work are suggested.

Thesis Supervisor: Nathaniel I. Durlach

Title: Senior Scientist of Electrical Engineering

Acknowledgments

First of all, I want to say I'm lucky to have Nat as my thesis advisor whose encouragement is the most inspiring reason for my persistence and hard work. And I also wish to express my deepest gratitude to him for his hard work and for all the academic and financial help I received from him when I was really in need of it.

I'm very grateful to Dr. Tom Wiegand, not only for the tremendous technical help, but also for his friendship which is so important for me.

I would also like to thank all members of the 7th floor for their smiles and cookies.

To my parents-the harbor of my heart for ever!

Contents

Chapter 1: INTRODUCTION

When a human user operates in VEs, alterations in sensory-motor loops will occur due to limits of current technology (e.g., alterations involving time delays or noise) or to intentional modifications introduced to enhance performance (e.g., simulating increased distance between the eyes to achieve improved visual depth perception or increased distance between the ears to achieve improved auditory localization). This thesis investigates the effects of one kind of alteration in visual sensory-motor loop: the effects of time delays on depth perception by motion parallax in VEs.

The human visual system uses a variety of different cues, including binocular parallax, monocular parallax, and motion parallax to judge depth and distance. Binocular parallax and monocular parallax are already extensively used in 3-D graphics, each with its own advantages and disadvantages (Ellis, 1991). However, motion parallax, with great potential in 3-D graphics, hasn't yet been fully exploited.

Motion parallax refers to the relative movement of images across the retina resulting from movement of the observer or of objects crossing the observer's field of vision. In order to realize 3-D images in VEs by means of motion parallax, movement of the user's head must be measured and that information must be transmitted to the computer to update the image

appropriately. Due to limited processing capability and transmission speed, some delay between movement and updating is unavoidable. However, the quantitative effects of delays of various magnitudes have not yet been adequately documented. And such knowledge is necessary in order to make suitable choices in designing VE systems.

Two experiments were performed with 6 human subjects in order to observe the effects of different delays on depth perception by motion parallax. The results show quantitatively how depth perception changes as delay is increased.

Chapter 2 presents background on VEs and on depth perception cues. Chapter 3 describes the experiment. Chapter 4 presents the results of the experiments. Chapter 5 provides some discussion of the experimental results and suggestions for future work.

Chapter 2: BACKGROUND

2.1 Virtual Environment systems (VEs)

VEs constitute an emerging field with still no generally accepted definition. They are computer-generated synthetic environments that can be highly realistic and familiar or highly unnatural and unfamiliar, with even the physical laws governing the behavior of objects in the environment changed (Warwick, Gray, & Roberts, 1993).

In general, a VE system consists of a human, a computer system, and a human-computer interface.

The human user obviously plays a central role in a VE system and many human-factor issues related to perception, cognition, and performance must be considered in designing VEs. The computer generates the virtual environment and contains both a description of each element in that environment and the rules that each element needs to follow. The human-computer interface provides communication between the computer and the human user and contains displays by means of which the computer presents information to the human users and controls by means of which the human users present information to the computer (Preece, 1995).

Corresponding to the various sensory modalities, there are various kinds of displays. In terms of frequency of use, both visual and audio displays are of dominant importance, followed by touch, and then smell. Taste has not yet been used in VEs. Displays that bypass the sensory organs and act directly on neural structures have also not yet been used. The most common control technologies used in current VEs include tracking technology, speech recognition and haptic devices.

VEs are complicated systems involving computers, interface devices and humans and there is a strong need for cooperation among many disciplines. Current work is mainly concerned with: 1) computer generation of VEs 2) improvement of human-machine interfaces; 3) study of relevant human-factor issues, and 4) development of communication systems that are adequate to support networking of VEs.

Among the many human-factor issues that must be considered in designing VEs are those related to how perception and performance are affected by limitations of the VEs. For example, with respect to the visual channel, factors such as contrast, resolution, stability, and field of view have an impact on the user's perception and performance. Our interest is the effects of time delay on depth perception by motion parallax.

Further material on VEs is available in Durlach & Mavor (1995), Kalawsky (1993), and Barfield & Furness (1995).

2.2 Depth Perception

2.2.1 Overview

Depth perception refers to the ability of a subject to perceive distance, or differences in distance, from the subject. In other words, it refers to the ability of a subject to perceive the third dimension, the dimension which is in the direction of the line of sight. The images on our retina are always 2 dimensional. How can we perceive a 3-D world using only 2-D images? It's a particularly complex issue. The human perceptual system is remarkable for the variety of cues, which include binocular disparity cues, monocular cues, and motion parallax that it can utilize in judgments of depth (Rogers & Graham, 1979; Ellis, 1991).

Binocular disparity is the most important cue of all the depth cues in regards to relative distance judgments in the near field (Surdick, & etc., 1994). Binocular disparity occurs because the two eyes are spaced horizontally apart by about 6.5 cm, and hence receive slightly different images of the world (see Figure 2.1). Normally, the visual system fuses the slightly different images and this fusion results in stereopsis. Although in many situations depth perception can be achieved by using stereopsis alone, stereopsis fails for most observers at distances exceeding about 500m. Also it is worth noting that not everyone can perceive depth by stereopsis: 5-10% of the population are stereoblind. These people still see depth, however, because they are able to utilize other cues.

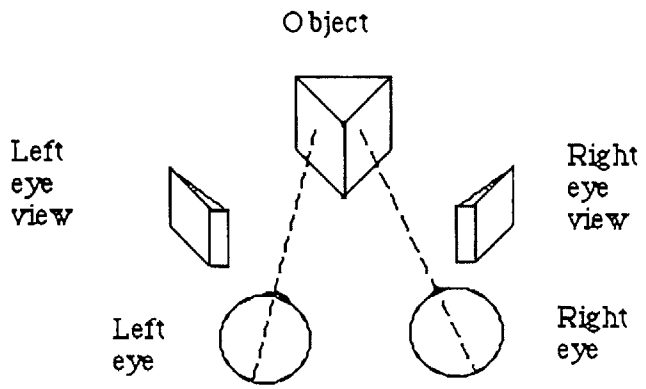


Figure 2.1 Binocular Disparity

Monocular cues, which enable a viewer to perceive depth even with one eye closed, include occlusion, linear perspective, relative size, color, brightness, contrast, shading, and texture gradient, etc. (Boff and Lincoln, 1988) Many of these cues are context dependent. For example, occlusion is useless unless two objects are placed so that one is at least partially in front of the other.

2.2.2 Motion Parallax Cue

Motion parallax refers to the relative movement of images across the retina resulting from movement of the observer or of objects crossing the observer's field of vision.

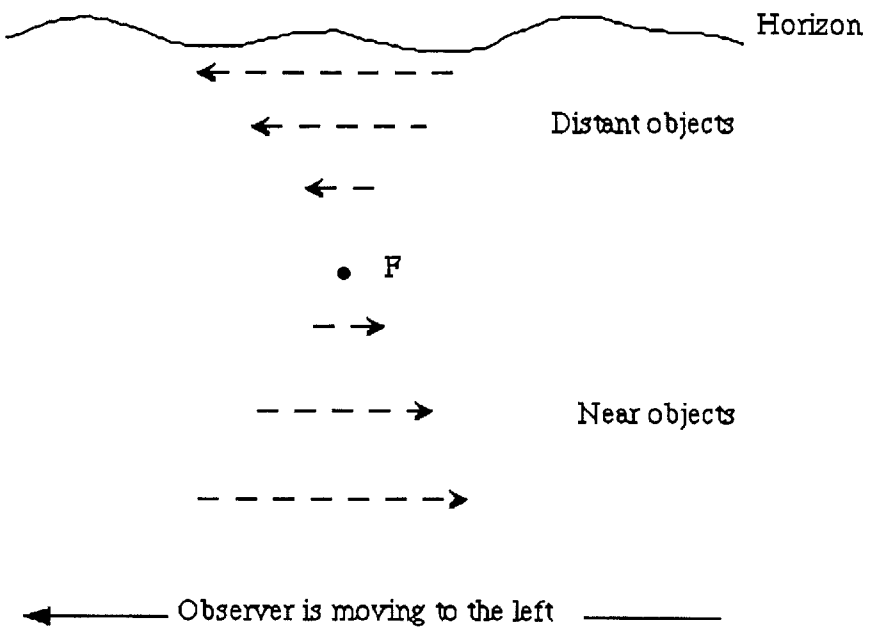


Figure 2.2 Motion parallax cue

In Figure 2.2, the observer is fixating at point F, and moving to the left. All objects farther than F will appear to move with the observer, while objects nearer than F will appear to move in the opposite direction. As indicated by the length of the dashed lines, objects more distant from F (either behind F or in front of F) will appear to move more rapidly than objects closer to F. The visual system uses the apparent direction and speed of motion of stationary objects to compute the distance of these objects relative to the fixation point F.

Motion parallax is one of the most important cues for depth perception. The experimental study of motion parallax dates back to the time of Helmholtz (1925). In 1950, J.J. Gibson (Gibson, 1950) proposed that a gradient of velocity is important in slant perception; after

that, there have been numerous studies using different types of gradients such as sine, triangle, sawtooth, and square waveforms. These studies can generally be divided into two classes: externally-produced motion parallax and self-produced motion parallax. In the first class, motion parallax is demonstrated on a stationary screen by moving two-dimensional patterns across it that correspond to the projections of a 3-D object as seen by a stationary observer. This form of motion parallax, which has been extensively investigated, is known as the kinetic depth effect (Braunstein, 1966; Kaufman, 1974). In the second class, motion parallax is demonstrated on a flat screen by changing a two-dimensional pattern according to lateral movement of the head (Rogers & Graham, 1979, Ullman, 1979, 1983). The main difference between the two classes is that in self-produced motion parallax, the depth perception involves not only visual information but also vestibular and kinesthetic information (Ono & Steinbach, 1990).

Further information on depth perception in general, and on motion parallax in particular, can be found in Goldstein (1999), Helmholtz (1925), and Rogers & Graham (1979).

Although some attention has been given to motion parallax in VE systems (e.g., see McKenna, 1992), there does not seem to be any previous study of how depth perception via motion parallax in VEs degrades as the delay is increased.

Chapter 3: EXPERIMENT

3.1 Overview

Computer generated random-dot patterns simulating the surface of one cycle of a vertically corrugated sinusoidal function were used as stimuli. The random-dot patterns and their movements were structured so that the middle value of the sinusoid always appeared in the plane of the screen, the upper half cycle appeared in front (or behind) the screen, and the lower half behind (or in front of) the screen. In all cases, the subject was required to move his or her head laterally and then to judge which half cycle of the sinusoid (the upper or the lower) stuck out in front of the screen. Two experiments were performed, one in which the head movement consisted of a single movement from middle to left, and a second in which the movement was more extensive.

3.2 Apparatus

The experimental hardware consisted of two main components: a headtracker for obtaining

the head position information and a controlling PC to which the information is reported. The functions of the PC are to calculate the relative movement of the subject from the position information, update the graphic pattern appropriately, and store the subject's responses.

The headtracker used in our experiment is the **3SPACE ™ magnetic** tracker composed of three components: a source to generate a magnetic field; a sensor to sample the field; and an electronics unit to perform all the required computing and interfacing functions. A more detailed description of the headtracker is given in Appendix A.

3.3 Stimuli

The set of stimuli involved variations over two parameters: magnitude of the sinusoidal function and time delay between the head movement and the movement of the random-dot pattern. Six values of each parameter were tested in the experiment: the magnitudes were 0.01, 0.08, 0.16, 0.32, 0.64 and 1.00 inches, and the delays were 55, 110, 220, 440, 880, and 1760 ms. For each of the 36 combinations of magnitude and delay, 16 trials were performed, leading altogether to 576 trials which were presented to the subject in random order. The reason for the random presentation was to force, to the extent possible, the subject to base his or her response on the perception of depth cues rather than other unavoidable cues. Also, the randomization served to disentangle the effects of amplitude and delay from learning and fatigue effects.

At the beginning of each trial (one trial constitutes the time from the beginning of moving the head to making a response), the computer generates a two-dimensional random-dot pattern composed of approximately 150 random dot units (A, B, ..., C in Figure 3.1), each of which is 27 pixels wide by 2 pixels high. The dot units are distributed over 17 rows (numbered from 0 to 16) with adjacent rows separated by 10 pixels. Only part of the dot unit (6-7 consecutive pixels wide by 2 pixels high) which we refer to as the dot, is visible at any time. The dot unit is the range over which the dot can move during each trial. Given a pixel size of 0.017 inch wide by 0.017 inch high, and a distance from eye to display of approximately 25 inches, one pixel subtends roughly 2.4 minutes of arc from the viewer's eye.

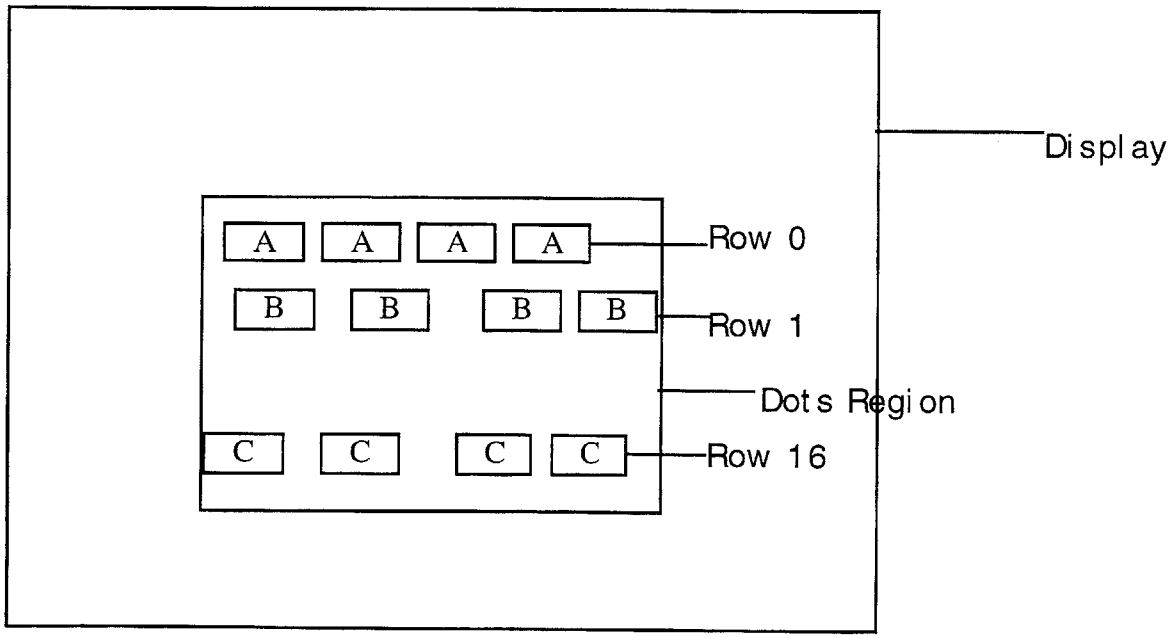


Figure 3.1 Dot Units Distribution Diagram

The movement of the dots is a function of the movement of head, the amplitude of the sinusoid, and the position of that dot on the sine-wave surface, the computation of which is described in Appendix B. In order to make the dot's movement smooth, an antialiasing technique was used in the experiment which increased the pseudo-resolution of the dot movement to 1/40 pixels. The basic idea of antialising and it's implementation is also given in Appendix B.

The delay was measured by two DOS functions: starttime() and endtime(). Because of the limited transmission and computation speeds in our system, a minimum delay of 55 ms occurred between the movement of the head and the updating of the random-dot patterns. The other 5 delays used (110 ms, 220 ms, 440 ms, 880 ms and 1760 ms) were implemented as described in Appendix B.

3.4 Experimental Procedure

Six subjects with normal or corrected-to-normal vision took part in the experiment. Before doing the experiment, the subjects filled out a consent form and answered screening questions (see Appendix C). They then put the headtracker cap on their head and sat about 25 inches in front of the display in a dark room. They were then asked to move their head from the left to the right and vice versa, and without receiving any further instructions, to report what they perceived. The purpose of this step was to see what would happen without giving the subjects any information about the 3-D structure. Subsequent to this report, the subjects were told that the stimuli presented to them were 3-D sine-wave surfaces.

In experiment 1, the task of the subjects on each trial was to move their heads back and forth from the left to the right (repeatedly if they wished) and then to press the "T" key if they perceived that the upper half cycle of the pattern was behind the display, and the "B" key if they perceived that the lower half cycle was behind the display. If they weren't sure, they were told to guess. In experiment 2, everything was the same except for the head movement: the subjects could only move their head from the middle to the left once for each trial. In neither experiment was any trial-by-trial feedback provided.

Chapter 4: RESULTS

All subjects said they perceived only individual moving dots before they were informed of the structure of the stimuli; however, after they were informed of the structure, i.e., of the existence of the sinusoid in the depth dimension, they all claimed to perceive it clearly. And after they had done the experiments, all of them confirmed that they perceived the depth clearly.

Tables 4.1 to 4.8 and Figures 4.1 to 4.8 summarize the stimulus-response data for the 6 subjects tested in Experiment 1 and 2 (3 subjects in Experiment 1 and 3 subjects in Experiment 2). For each combination of amplitude and delay, the curves give the number of correct responses out of the 16 trials presented for that combination of stimulus values. The upper graphs show the number of correct responses as a function of delay with amplitude as a parameter, and the lower graphs show the number of correct responses as a function of amplitude with delay as a parameter. Graphs which show the results averaged over subjects are presented after the graphs for the individual subjects.

In general, it appears that the discrimination threshold in these two experiments lies in the region from 0.01 inches to 0.08 inches. Whereas random guessing corresponds to 50% correct, the average percent correct scores in the two experiments at 0.01 inches and 0.08

inches are: 52% (Experiment 1, 0.01 inches), 69% (Experiment 1, 0.08 inches), 58% (Experiment 2, 0.01 inches), and 71% (Experiment 2, 0.08 inches). According to the formula given in Appendix B, an amplitude of 0.01 inches corresponds to a maximum dot movement of 0.36 minutes of arc, and an amplitude of 0.08 inches corresponds to a maximum dot movement of 2.9 minutes of arc (assuming the range of head movement is 6 inches). Compared with the results of previous similar research (Rogers & Graham, 1979), this result appears reasonable.

Intersubject variations appear quite small for all cases, except for subject 6 in Experiment 2: whereas the results for a delay of 1760 ms for both subjects 4 and 5 go well below 50% correct at the large amplitudes, this is not the case for subject 6.

In both Experiment 1 and 2, the dependence of performance on delay remains relatively flat in the region 55 ms to 220 ms. In this region of delay, performance increases relatively steadily from near threshold at 0.01 inches to near perfect at 0.32 inches and beyond. The average result over all data in the region 55 ms to 220 ms from both experiments is 91% correct at 0.32 inches and 90% correct at 1.0 inches.

The main differences between the results of the two experiments concern the effects of delays for large amplitudes (well above threshold) at delays in the region 440 ms to 1760 ms. In Experiment 1, performance decreases for delays between 220 ms and 880 ms to distinctly below chance (50% correct) and than bounces up again at 1760 ms. In Experiment 2, the equivalent data continues to decrease monotonically from 440 ms to 1760 ms and gets substantially below chance at 1760 ms.

Table 4.1 Data of Subject 1

	0.01	0.08	0.16	0.32	0.64	1.00
55	10	11	13	14	15	14
110	11	11	11	14	15	14
220	12	10	10	14	16	11
440	6	10	5	6	5	11
880	8	5	7	3	2	4
1760	7	4	7	8	9	11

Figure 4.1 (a)

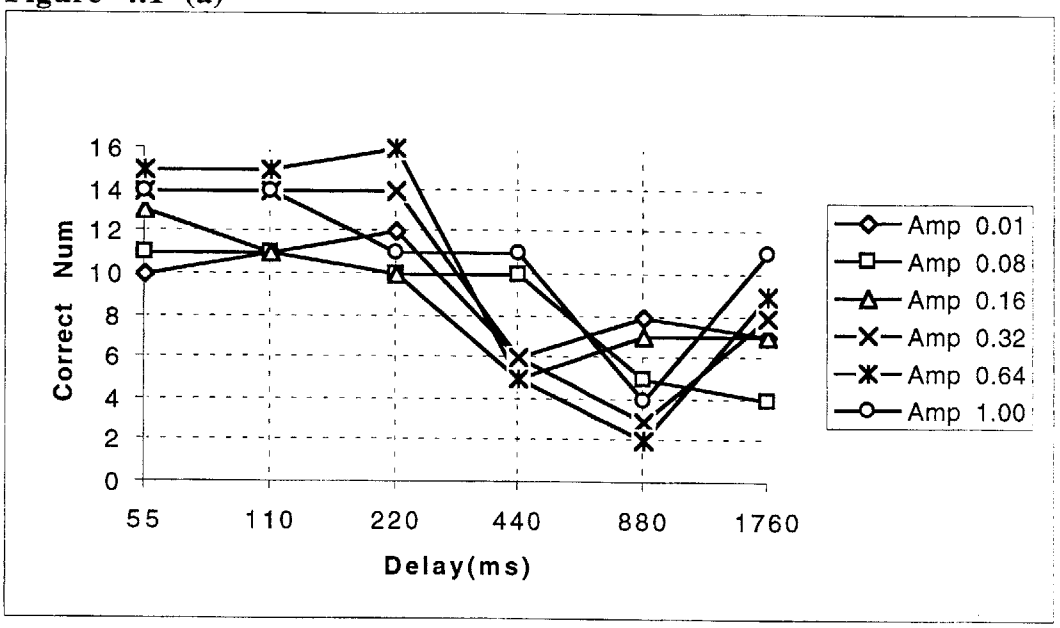


Figure 4.1 (b)

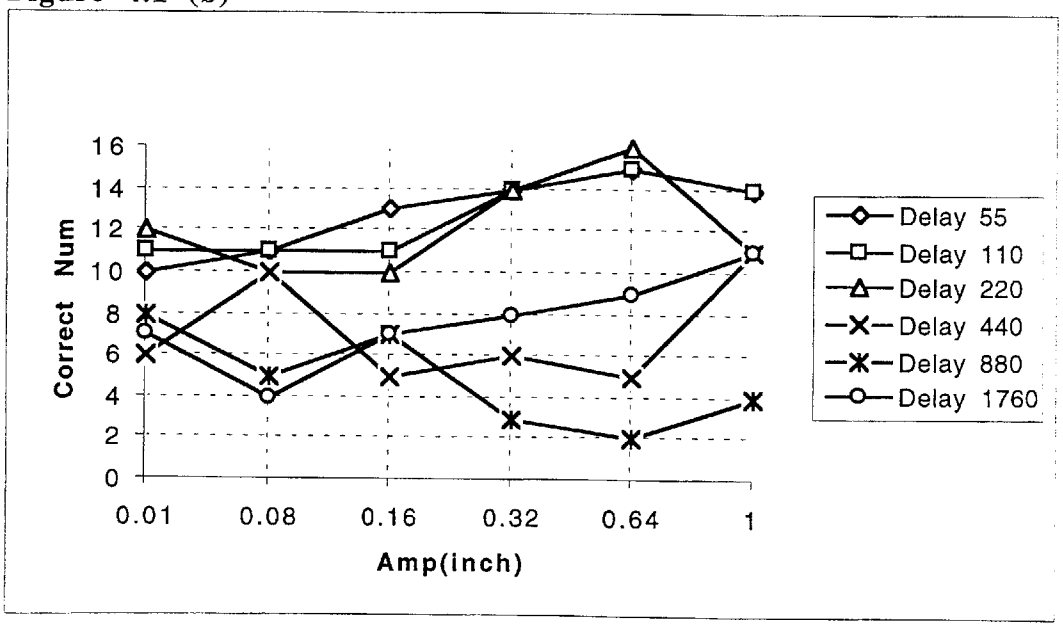
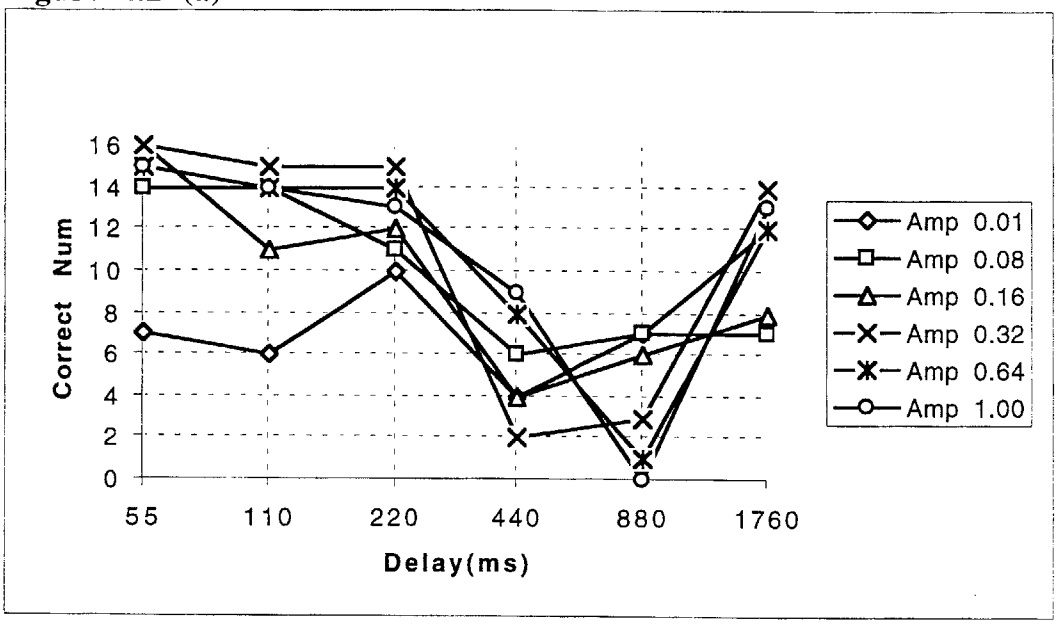


Table 4.2 Data of Subject 2

	0.01	0.08	0.16	0.32	0.64	1.00
55	7	14	16	16	15	15
110	6	14	11	15	14	14
220	10	11	12	15	14	13
440	4	6	4	2	8	9
880	7	7	6	3	1	0
1760	12	7	8	14	12	13

Figure 4.2 (a)



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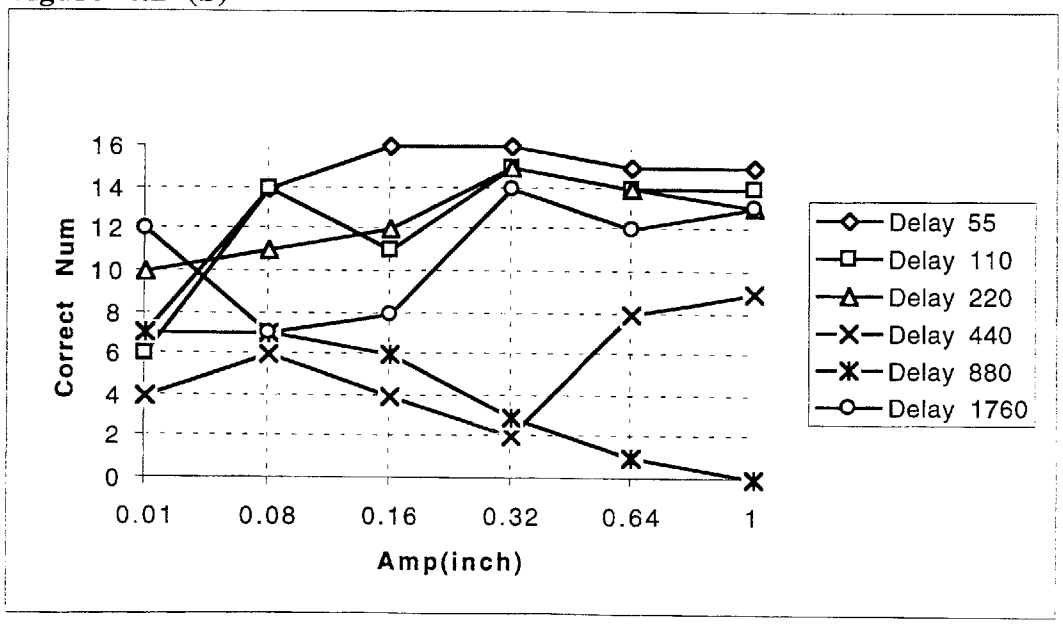


Table 4.3 Data of Subject 3

	0.01	0.08	0.16	0.32	0.64	1.00
55	8	8	13	13	14	16
110	10	6	8	16	14	16
220	3	10	10	14	14	14
440	5	10	5	6	8	14
880	8	8	3	5	5	0
1760	6	10	14	10	14	12

Figure 4.3 (a)

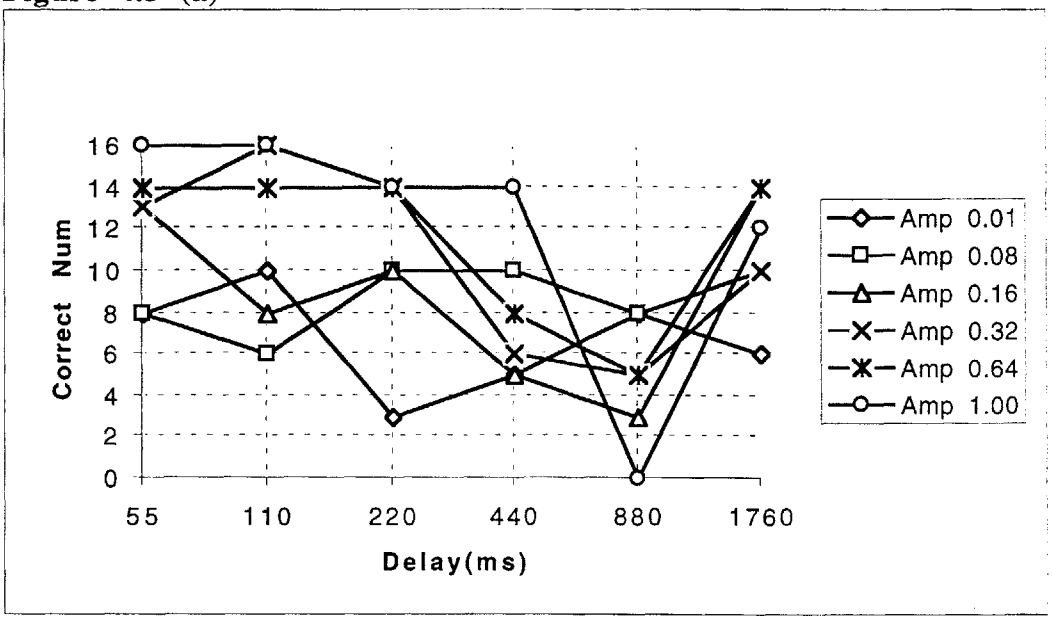


Figure 4.3 (b)

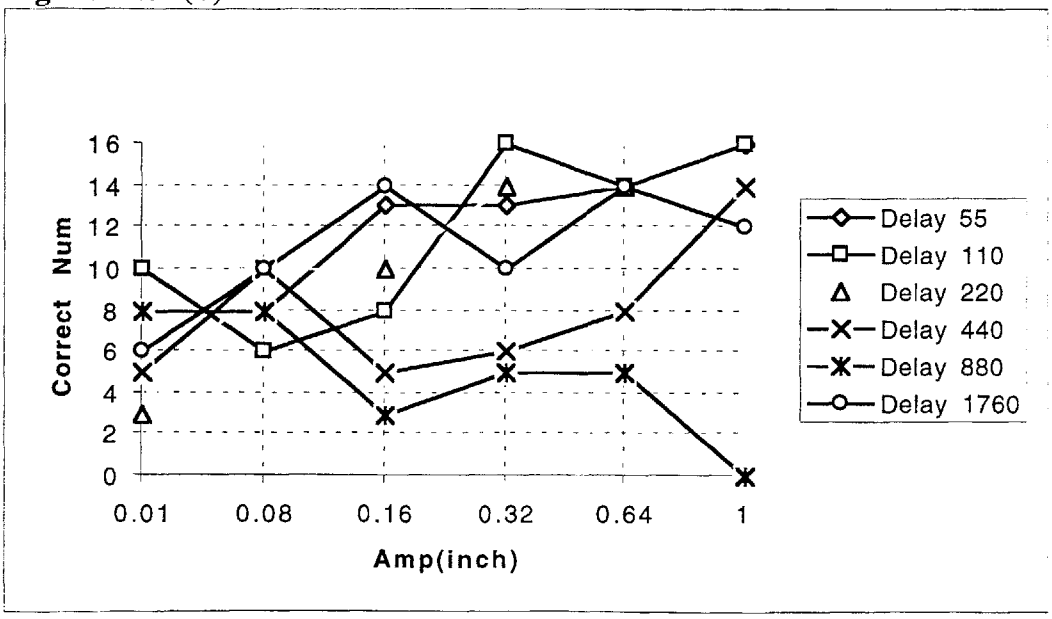


Table 4.4 Average Data of Experiment 1

	0.01	0.08	0.16	0.32	0.64	1.00
55	8.3	11	14	14.3	14.7	15
110	9	10.3	10	15	14.3	14.7
220	8.3	10.3	10.7	14.3	14.7	12.7
440	5	8.7	4.6	4.7	7	11.3
880	7.7	8.3	5.3	3.7	2.7	1.3
1760	8.3	7	9.7	10.7	11.7	12

Figure 4.4 (a)

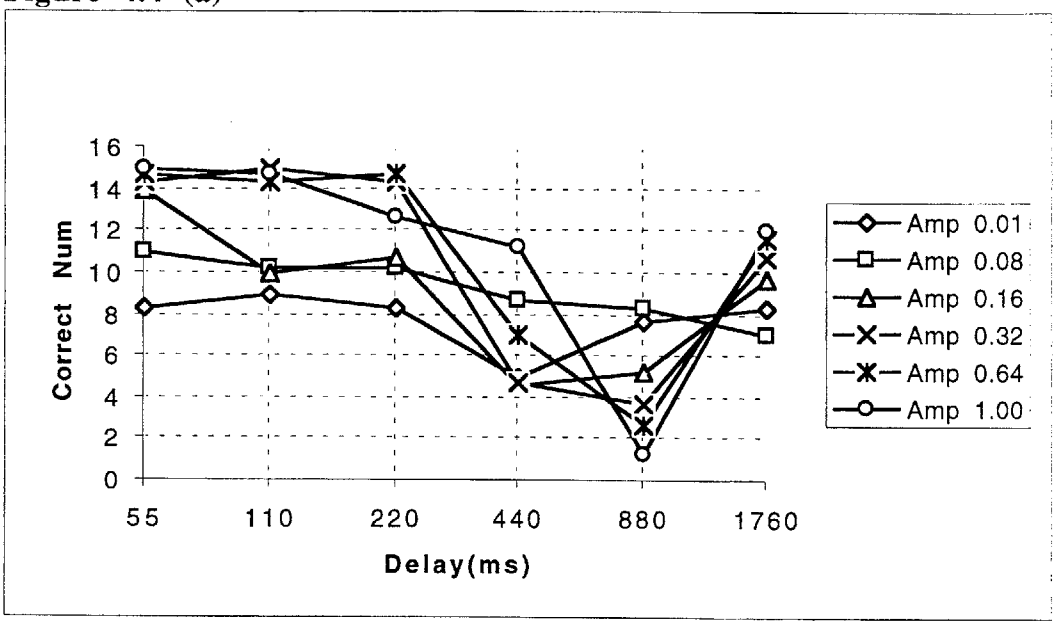


Figure 4.4(b)

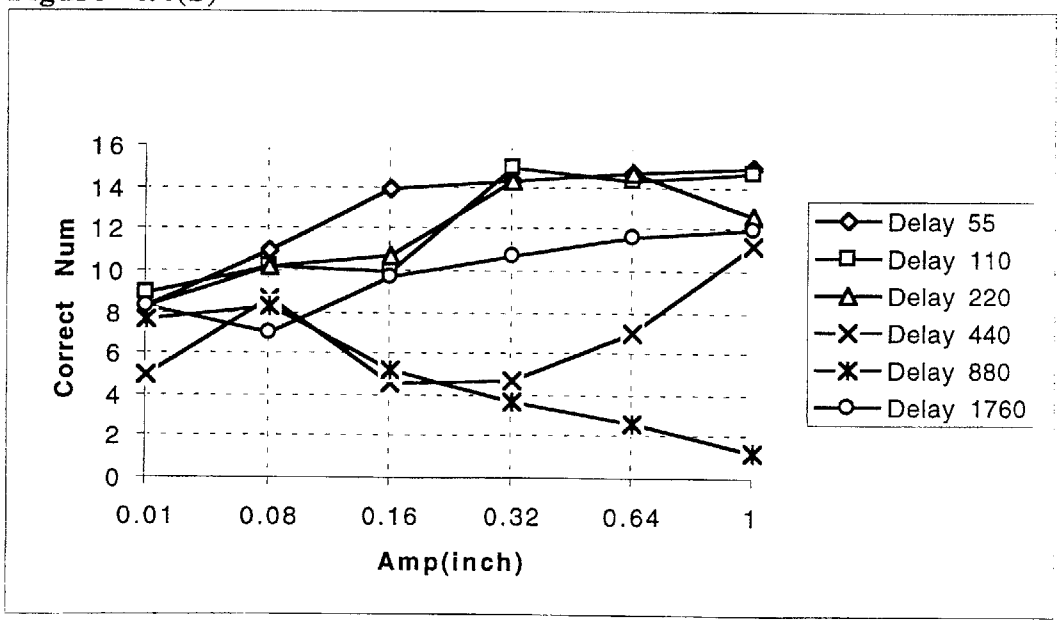


Table 4.5 Data of Subject 4

	0.01	0.08	0.16	0.32	0.64	1.00
55	10	11	16	15	15	13
110	7	14	12	15	12	11
220	6	12	13	11	15	13
440	7	13	15	15	10	10
880	9	5	12	8	12	13
1760	8	6	3	4	4	1

Figure 4.5 (a)

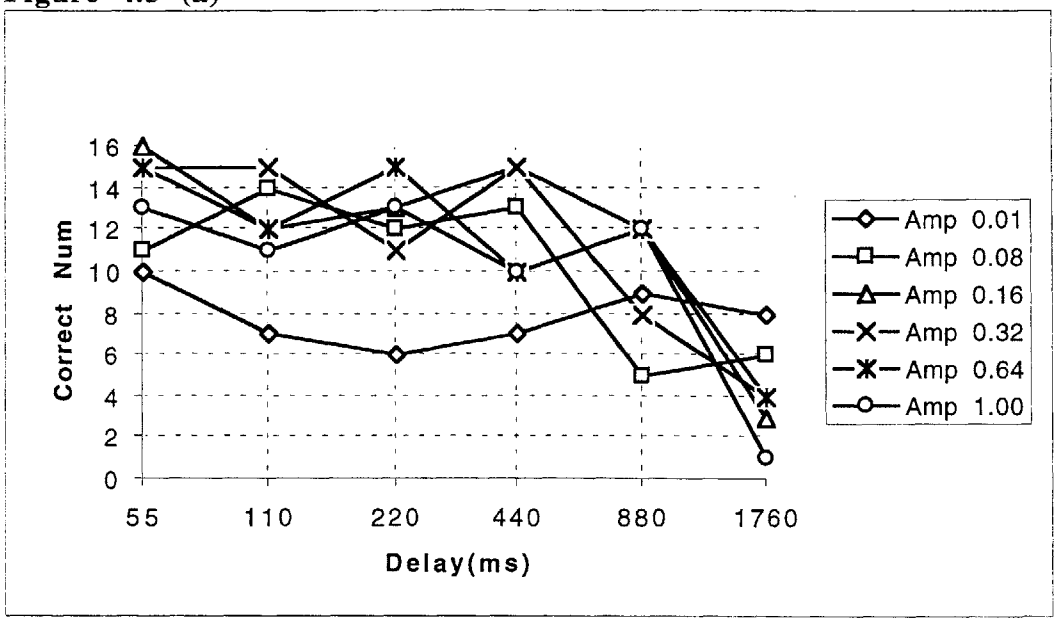


Figure 4.5 (b)

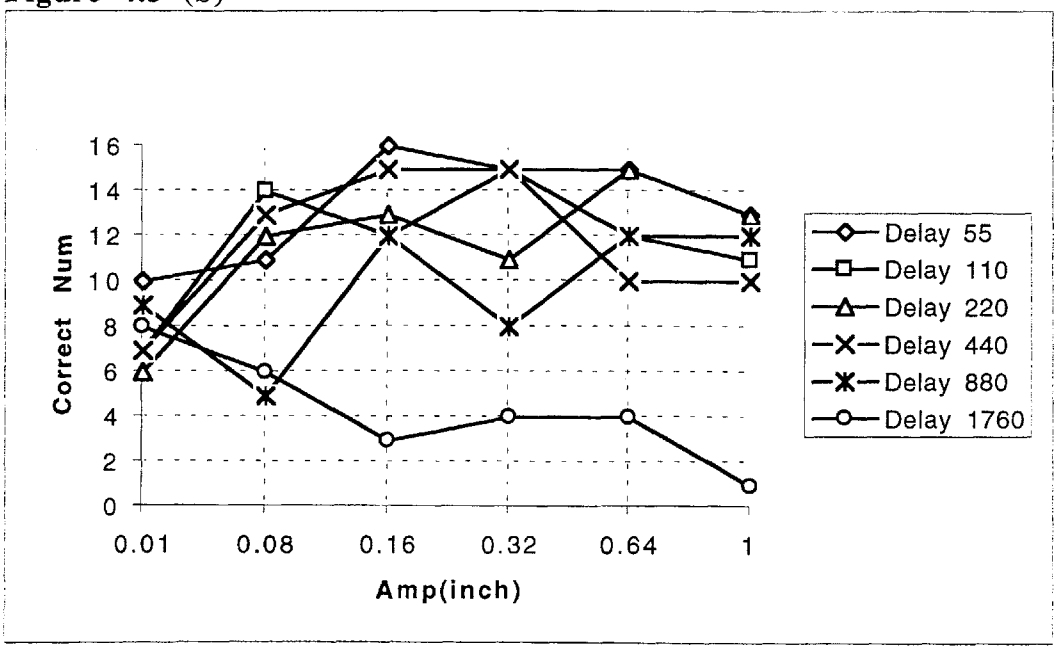


Table 4.6 Data of Subject 5

	0.01	0.08	0.16	0.32	0.64	1.00
55	8	12	12	15	15	16
110	6	10	12	16	15	16
220	9	13	15	15	16	16
440	8	11	14	16	16	15
880	7	9	11	10	13	14
1760	8	5	5	1	0	3

Figure 4.6 (a)

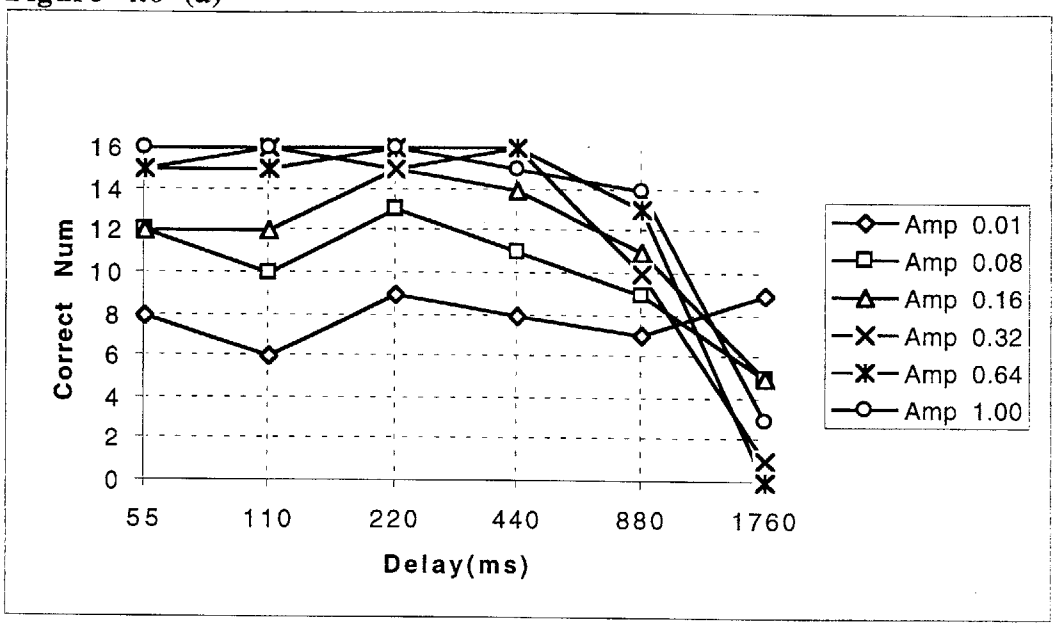


Figure 4.6 (b)

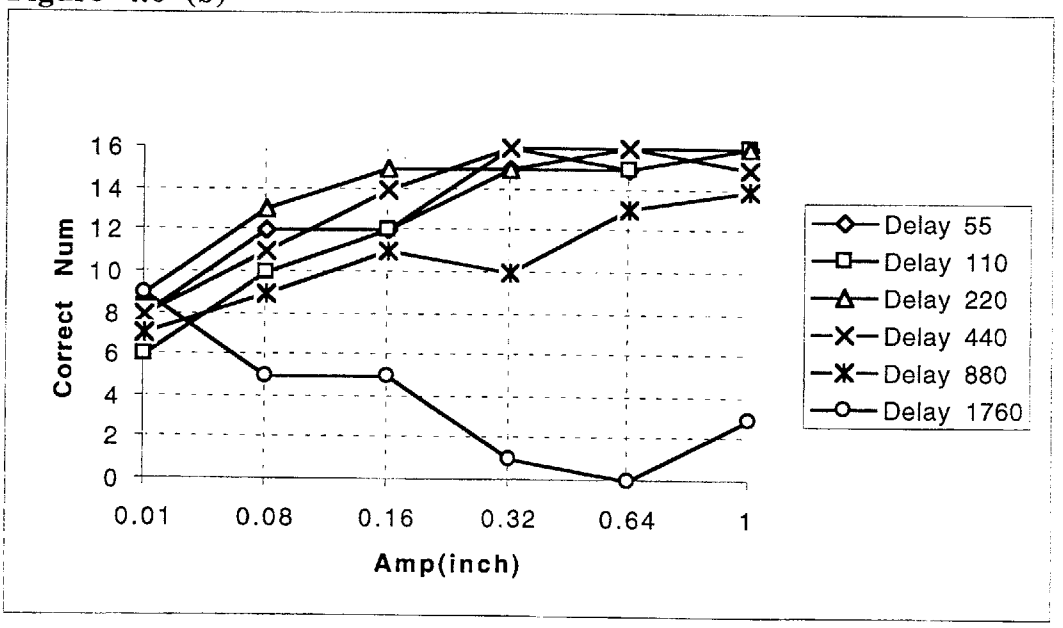


Table 4.7 Data of Subject 6

	0.01	0.08	0.16	0.32	0.64	1.00
55	10	11	14	16	16	16
110	8	7	13	15	16	16
220	11	10	9	14	15	16
440	7	10	10	14	14	15
880	10	8	10	8	9	11
1760	9	5	8	7	8	8

Figure 4.7 (a)

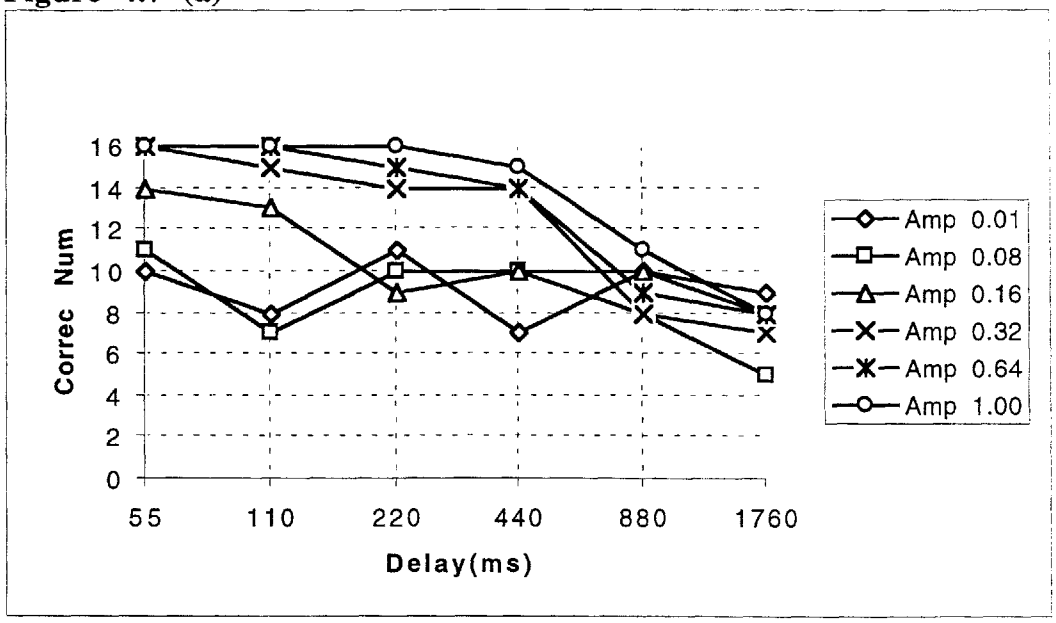


Figure 4.7 (b)

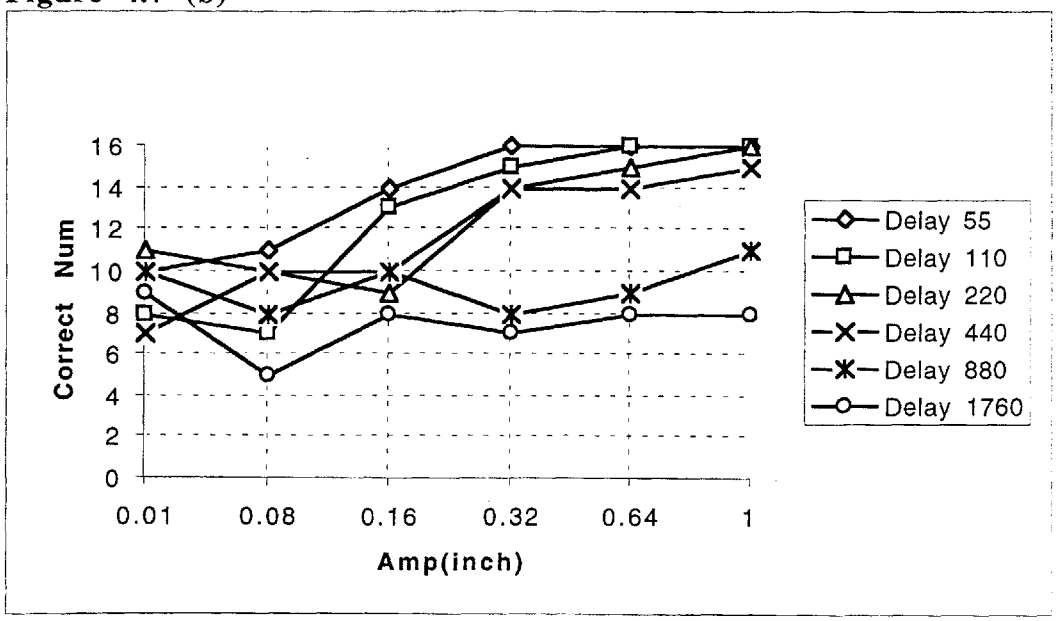


Table 4.8 Average Data of Experiment 2

	0.01	0.08	0.16	0.32	0.64	1.00
55	9.3	11.3	14	15.3	15.3	15
110	7	10.3	12.3	15.3	14.3	14.3
220	8.7	11.6	12.3	13.3	15.3	15
440	7.3	11.3	13	15	13.3	13.3
880	8.7	7.3	11	8.7	11.3	12.7
1760	8.3	5.3	5.3	4	4	4

Figure 4.8 (a)

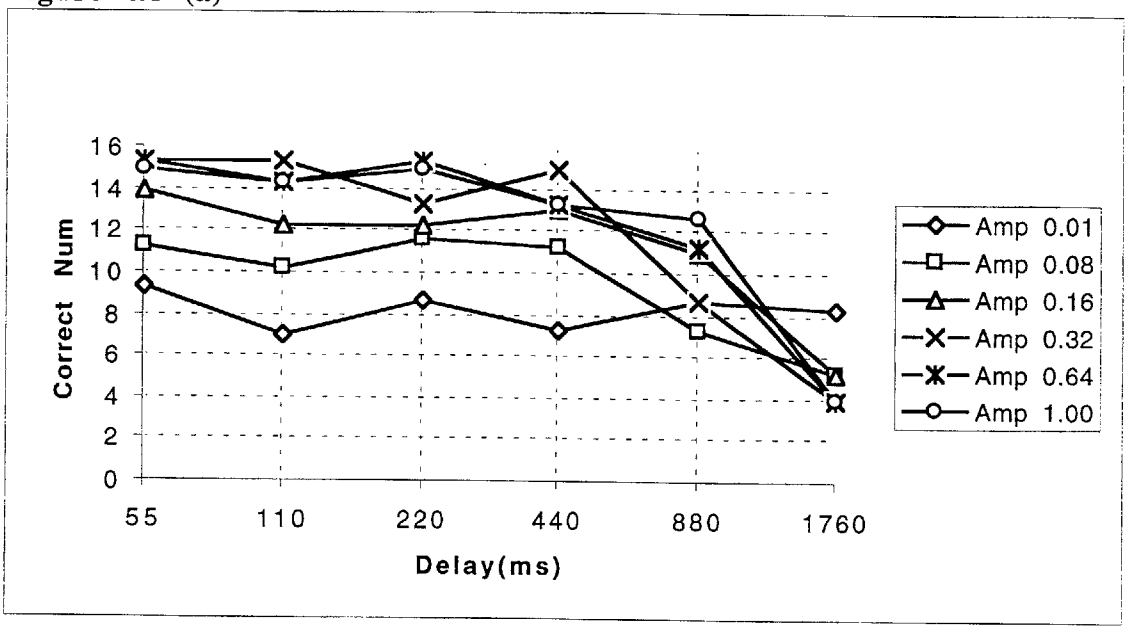
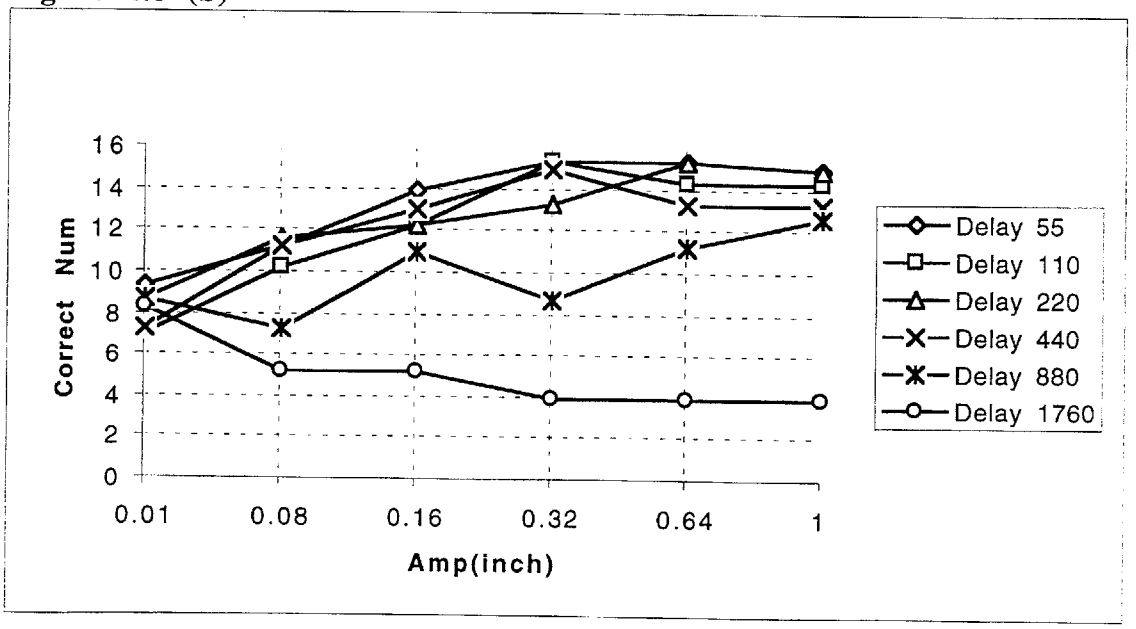


Figure 4.8 (b)



Chapter 5: DISCUSSION

The results of both experiments indicate that delays less than 220 ms do not degrade depth perception. Because delays that occur in most single-user VE systems are smaller than 220 ms, these results imply that delay is not a problem for depth perception via motion parallax in such systems. However, there may be some degradation in networked systems, where both the magnitude and the variation of delay can be large.

According to the results of Experiment 1 for large amplitudes (e.g., amplitudes $\geq$ 0.32 inches), performance goes well below chance (50% correct) at 880 ms and then rises up well above chance again at 1760 ms. The data at 880 ms indicate that discrimination was still possible at this delay, but that the response coding was inverted. This result is possibly due to the quasi cyclic head motion that occurred in this experiment. If the delay is appropriately related to the phase of the head movement, and the subject does not take account of the delay, such inversion would necessarily take place. In order to check this hypothesis, if would be necessary to record the head movement and examine the relation between head movement and response.

In contrast to Experiment 1, the performance in Experiment 2, where the head movement

consisted of only a quarter cycle (center to left), decreases monotonically with no dip at 880 ms. However, the results for large amplitudes (amp $\geq$ 0.01 inches) are substantially less than chance at 1760 ms (the average results here are 28% correct). This problem has little practical importance because very few, if any, VE systems are going to have delays of this magnitude. However, it is very puzzling from a scientific point of view.

Immediate future work is needed in the following areas: Recording and examination of head movements (range, velocity, and duration), analysis of how judgments are influenced by measured head movements, and development of a model relating responses to stimuli (amplitude, delays) and head movements (range, velocity, duration). Aside from determining the cause of performance becoming worse than chance, it would be useful to determine in detail how performance is influenced by the range, velocity and duration profile of the head movement.

Bibliography

Barfield, W., & Furness, T. A. (1995). *Virtual Environments and Advanced Interface Design.* New York: Oxford university press.

Boff, K. R., & Lincoln, J. E. (1988). *Engineering Data Compendium: Human Perception and Performance.* 3 vols. Vol. 2. Ohio : Harry G. Armstrong Aerospace Medical Research Laboratory.

Braunstein, M. L. (1966). Sensitivity of the observer to transformations of the visual field. *Journal of Experimental Psychology,* v 72, 683-689.

Durlach, N. I., & Mavor, A. S. (1995). *Virtual reality scientific and technological challenges.* Washington, D.C. : National Academy Press.

Ellis, S. R. (Ed) (1991). *Pictorial communication in virtual and real environments.* New York : Taylor & Francis.

Gibson, J. J. (1950). *Perception of the visual World.* Boston: Houghton Mifflin.

Goldstein, E. B. (1999). *Sensation and Perception.* Pacific Grove, CA: Brooks/Cole Publication.

Helmholtz, H. V. (1925). *Helmholtz's Treatise on Physiological Optics.* New York: Dover Publications.

Kalawsky, R. S. (1993). *The science of virtual reality and virtual environments.* Reading, MA: Addison-Wesley.

Kaufman, L. (1974). *Sight and Mind: An Introduction to Visual Perception.* New York: Oxford University Press.

Krueger, M. W. (1991). *Artificial Reality II.* Reading, MA: Addison-Wesley.

Mack, A. (1998). *Inattentional blindness.* Cambridge, MA : MIT Press.

McKenna, M. (1992). Interactive Viewpoint Control and Three-Dimensional Operations. *Proceedings of the 1992 Symposium on Interactive 3D Graphics, cambridge, ma,* 53-56.

Ono, H., & Steinbach, M. J. (1990). Monocular stereopsis with and without head movement. *Perception & Psychophysics,* 48(2), 179-187.

Pfautz, J. D. (1996). *Distortion of Depth Perception in Virtual Environment Application.* B.S. M. E., M.I.T.

Preece, J. (1995). *Human-computer interaction.* Reading, MA: Addison-Wesley.

Rogers, B., & Graham, M. (1979). Motion parallax as an independent cue for depth perception. *Perception,* v 8, 125-134.

Surdick, R. T., Elizabeth, T. D., Robert, A. K., Gregory, M. C., Alexander, S., Larry, H., & Kelly, E. (1994). *Relevant cues for the visual perception of depth: is where you see it where it is?* Paper read at Human Factors and Ergonomics Society 38th Annual Meeting.

Tittle, J. S., & Braunstein, M. L. (1993). Recovery of 3-D shape from binocular disparity and structure from motion. *Perception &Psychophysics,* 54(2), 157-169.

Ullman, S. (1979). *The interpretation of visual motion.* Cambridge, MA: MIT Press.

Ullman, S. (1983). *Computational studies in the interpretation of structure and motion: summary and extension.* Cambridge, MA: MIT A.I..

Ullman, S. (1983). *Maximizing rigidity: the incremental recovery of 3-D structure from rigid and rubbery motion.* Cambridge, MA: MIT Press.

Warwick, K., Gray, J., & Roberts D. (ED) (1993). *Virtual reality in engineering.* London: Institution of Electrical Engineers.

Appendix A: 3SPACE Tracker

1. General Description

A 3SPACE Tracker system is composed of three essential components: a source to generate a magnetic field; a sensor to sample the field; and an electronics unit to perform all required computing and interfacing functions.

The source and the sensor are each constructed by winding three orthogonal coils around ferrite cores. Each assembly is then potted in epoxy to form a virtually unbreakable unit that plugs into the front of the electronics unit via an attached cable.

In a typical system implementation, the source is fixed on a non-metallic surface in a predetermined position and attitude, and becomes the frame of reference for all position and orientation measurements. The sensor may then be mounted on any convenient, non-metallic surface of the movable object, and is free to be moved throughout the usable 3SPACE Tracker operational hemisphere.

The system electronics unit is comprised of an analog board, a digital processor board and a switching power supply. The analog board contains circuitry to generate and sense the magnetic fields and digitize the sensed analog signals. The digital processor board controls the analog board, performs all necessary computations, and communicates with the outside world.

2. Specification

- Angular Coverage: Azimuth = ± 180°
  Elevation = ± 180°
  Roll = ± 180°

- Operational Envelope: A hemispherical shell centered about the source with a minimum radius of 8 inches and a maximum of 31.3 inches referenced to the source. Operation up to 10 feet is possible with reduced accuracy.

- Static Accuracy: Sensor orientation is determined to within 0.8° CEP at the 95% confidence level throughout a compensated operational envelope.

- Translational Accuracy: Translational Accuracy for x, y, and z is within 0.25 inches RMS of the true value.

- System Resolution: Angular = 0.1°
  Translational = 0.05 inches

- Measurement Rate: 60 measurements/sec

- Outputs:

Serial ASCII, 9600 Baud, asynchronous, RS-232C, 8 data bits/character, 1 stop bit/character
Serial ASCII, 19.2K Baud, asynchronous, RS-232C, 8 data bits/character, 1 stop bit/character
Serial binary, 9600 Baud, asynchronous, RS-232C
Serial binary, 19.2K baud, asynchronous, RS-232C

- Temperature: Operating under +10°C to +40°C

- Power: 90 to 130 V(AC), 47 to 63 Hz at 3/4 A RMS max.

Appendix B: Generation of the Stimuli

As pointed out in chapter 3, at the beginning of each trial, the PC produces an initial random-dot pattern which is composed of 17 rows of dot units, with each dot unit 27 pixels wide by 2 pixels high; then, the position of each dot (the visible part of the dot unit), which is 6-7 pixels wide by 2 pixels high, is updated according to the head movement of the subject to simulate the appearance of the dot on a 3-D corrugated sine-wave surface. This section describes: (1) how to compute the dot movement according to the head movement, (2) how to apply anti-aliasing to smooth the dot movement, and (3) how to control the delay between the head movement and the updating of the pattern.

1. Computation of the dot movement

The movement M_D of the dots is a function of the movement M_H of the head, the amplitude Amp of the sinusoid, and the row I to which the dot belongs.

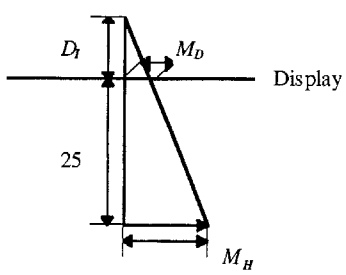


Figure B-1: The relation between the dot movement and the head movement

D_I is the distance from the dot on the I th row of the sine-wave surface to the display. Because the middle value of the sinusoid always appeared on the plane of the display, and the 17 rows of dots are spaced equally across the surface, the absolute value of D_I is equal to $Amp\sin(2\pi I/16)$. The value of D_I is positive, when the dot is behind the plane of the display.

The subject sat 25 inches from the display in the experiment. From Figure B-1, it is easy to see that $M_D/M_H = D_I/(D_I+25)$. Given the amplitude of the sinusoid, the head movement of the subject, the row to

which the dot belongs, and using an approximation that all dots on the same row have the same movement, we can calculate the movements for dots on different rows by the formula given above.

2. Antialiasing

Before antialiasing was included, at the beginning of each trial, the position of each dot unit (which remained fixed for the trial), was selected by the PC, and each pixel of the dot unit was initially assigned a color as in Table B-1.

Table B-1.

Row #	0, 8, 16	1, 7	2, 6	3, 5	4	9, 15	10, 14	11,13	12
Color #	0 ~ 26	27 ~53	54 ~ 80	81~ 107	108~134	135~161	162~188	189~215	216~242

Each color was assigned an intensity initially. For example, the colors for row 0, 8, and 16 were initially assigned the intensities shown in Table B-2.

Table B-2.

color #	0~9	10	11	12	13	14	15	16~26
Intensity	0	20	40	60	60	40	20	0

We can make the dot move by shifting the intensity distribution. For example, if the colors for row 0, 8, and 16 were assigned the intensities shown in Table B-3. The dots on row 1 would be shifted to the right by one pixel.

Table B-3.

color #	0~10	11	12	13	14	15	16	17~26
Intensity	0	20	40	60	60	40	20	0

The method described above caused the dot movements to appear jerky. In order to make the dot move smoothly, an antialiasing technique was introduced in this experiment. The basic idea is: (1) divide the required dot movement M_D (unit is pixel) into two parts: I , the maximum integer which is less than M_D; and P, the maximum integer such that $P/40$ is less than $(M_D - I)$,

(2) shift the intensity distribution of the dot I pixels and assign an appropriate distribution according to P. Table B-4 outlines the intensity distribution sets we used in the experiments (which yield a pseudo-resolution of the dot movement equal to 1/40 pixels).

Table B-4

P	$I_{p,0}$	$I_{p,1}$	$I_{p,2}$	$I_{p,3}$	$I_{p,4}$	$I_{p,5}$	$I_{p,6}$
0	20	40	60	60	40	20	0
1	19	39	59	60	40	20	0
2	19	39	59	60	41	21	1
3	18	38	58	60	41	21	1
4	18	38	58	60	42	22	2
5	17	37	57	60	42	22	2
6	17	37	57	60	43	23	3
7	16	36	56	60	43	23	3
8	16	36	56	60	44	24	4
9	15	35	55	60	44	24	4
10	15	35	55	60	45	25	5
11	14	34	54	60	45	25	5
12	14	34	54	60	46	26	6
13	13	33	53	60	46	26	6
14	13	33	53	60	47	27	7
15	12	32	52	60	47	27	7
16	12	32	52	60	48	28	8
17	11	31	51	60	48	28	8
18	11	31	51	60	49	29	9

19	10	30	50	60	49	29	9
20	10	30	50	60	50	30	10
21	9	29	49	60	50	30	10
22	9	29	49	60	51	31	11
23	8	28	48	60	51	31	11
24	8	28	48	60	52	32	12
25	7	27	47	60	52	32	12
26	7	27	47	60	53	33	13
27	6	26	46	60	53	33	13
28	6	26	46	60	54	34	14
29	5	25	45	60	54	34	14
30	5	25	45	60	55	35	15
31	4	24	44	60	55	35	15
32	4	24	44	60	56	36	16
33	3	23	43	60	56	36	16
34	3	23	43	60	57	37	17
35	2	22	42	60	57	37	17
36	2	22	42	60	58	38	18
37	1	21	41	60	58	38	18
38	1	21	41	60	59	39	19
39	0	20	40	60	59	39	19
40	0	20	40	60	60	40	20

3. Delay control

Due to the limited communication and computation speed, there is a minimum 55 ms delay between the movement of the head and the updating of the pattern which is chosen as the minimum delay. The other 5 delays (110 ms, 220 ms, 440 ms, 880 ms and 1760 ms) were implemented by 5 queues with 1, 3, 7, 15, and 31 memory units respectively. All the queues were initially set to 0. The PC updated the pattern according to the head movement information stored at the beginning of the queue, shifted the information stored in the rest of the memory units forward by one unit, and stored the current head movement information in the last memory unit.

Appendix C: Subject Forms

1. Subject Screening Questions

Sensorimotor Loop Subject Screening Questions

to be filled out by the experimenter

Subject ID code:_____ **Date:**____/____/_____

Gender:_____ **Age:**_____ **First Language:**_____

Handedness: in general: right [ ] left [ ] ambidextrous [ ]

	Completely left	Mostly left	Ambi-dexterous	Mostly right	Completely right
handwriting	[ ]	[ ]	[ ]	[ ]	[ ]
scissors	[ ]	[ ]	[ ]	[ ]	[ ]
screwdriver	[ ]	[ ]	[ ]	[ ]	[ ]
toothbrush	[ ]	[ ]	[ ]	[ ]	[ ]
computer mouse	[ ]	[ ]	[ ]	[ ]	[ ]
TV remote control	[ ]	[ ]	[ ]	[ ]	[ ]
joystick	[ ]	[ ]	[ ]	[ ]	[ ]
paddle sports	[ ]	[ ]	[ ]	[ ]	[ ]

Any visual disability/impairment? No [ ] Yes [ ]
if yes, describe:

Visual Acuity: Normal [ ] Corrected [ ] (glasses [ ] contact lenses [ ])
Corrected Acuity:___/___ Uncorrected Acuity:___/___.

Eye dominance test:

Right Aligned	Left Aligned	Mostly L.A.	Neither Aligned	Mostly R.A.
[ ]	[ ]	[ ]	[ ]	[ ]

Neurological or muscular abnormalities? No [ ] Yes [ ]
if yes, describe:

Does the subject seem to be in a normal state of attentiveness, coherence, wakefulness, and coordination?

Video Game Experience:

	None	A little	Some	A lot	Expert
Childhood:	[ ]	[ ]	[ ]	[ ]	[ ]
Recent:	[ ]	[ ]	[ ]	[ ]	[ ]

Previous VR or teleoperator experience of any kind?

Does the subject have a valid driver's license? Yes [ ] No [ ]

Additional Comments:

2. Consent Form

V.E.T.T./Sensorimotor Loop Subject Consent Form

to be read and signed by the subject

- Participation in this experiment is entirely voluntary and you may choose to stop at any time. All information that you provide to us is strictly confidential, and your data will be processed anonymously.

- You are entitled to an explanation of the procedures that are followed, and the purpose of these procedures. Accordingly, the experimenter will answer any questions that you may have regarding these procedures.

- The broad purpose of this study is to investigate ways in which Virtual Environment (VE) technology can be used for training. To accomplish this task, we are exploring the effects of alterations in sensorimotor loops on human performance. Briefly, this involves making judgements about, or performance of, various simple tasks within a virtual environment, and automatically collecting subject response data. The tasks are performed using a manually operated response buttons and manipulanda. You will have the opportunity to rest between conditions, but you must maintain full attention while the experiment is running. The entire experiment should last about an hour and a half.

- As a subject in these experiments, a visual display will be presented to you. You will be given instructions explaining how to interact with and/or make judgements about this display. In some presentations, the visual representation will be distorted, the response of the system may be temporally altered (e.g. delayed) and multiple stimulus modalities may be invoked (e.g. audio, touch, etc.). These options, and the specific tasks and end states that we describe to you, constitute the experimental conditions we are studying.

- The risks involved in this study are negligible, the equipment used either meets the safety requirements for commercially available home entertainment equipment, and/or incorporates fail-safe protective mechanisms. The level of physical and psychological stress is also minimal. However, you may discontinue your participation at any time should you so decide.

Standard MIT disclaimer:

In the unlikely event of physical injury resulting from participation in this research, I understand that medical treatment will be available from the MIT medical department, including first aid emergency treatment and follow-up care as needed, and that my insurance carrier may be billed for the cost of such treatment. However, no compensation can be provided for medical care apart from the foregoing. I further understand that making such medical treatment available, or providing it, does not imply that such injury is the investigator's fault. I also understand that by my participation in this study I am not waiving any of my legal rights. (Further information may be obtained by calling the Institute's Insurance and Legal Affairs office at 253-2822.)

I understand that I may contact the Chairman of the Committee on the Use of Humans as Experimental Subjects, MIT 253-6787 if I feel that I have been treated unfairly as a subject.

I have read and understood the above statements and agree to participate as a subject in these experiments.

Signature:_____ **Date:**_____

Printed Name:_____